For more negative values of V_{gr}, the device is brought into the accumulation mode and the trap sites begin to become neutralized very rapidly (point 4). In all cases, the trap sites close to the metal interface remain charged positively throughout the entire range of bias voltages. The justification for the model and its interpretation is the close correlation between computed and measured data over the entire range of bias voltages.

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Liquid phase epitaxy of GaAlAs on GaAs substrates with fine surface corrugations

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Liquid phase epitaxy of GaAlAs was performed on GaAs fine surface corrugations. By optimizing the growth conditions, GaAlAs layers were grown successfully with only minimal meltback.

An increasing number of proposed and demonstrated optical devices have been described recently which depend on the introduction of a periodicity into a dielectric waveguide. One of the most promising techniques for generating the periodicity involves the mechanical corrugation on a submicron scale of the air interface of a dielectric waveguide.[1] This technique has been applied to grating couplers,[1,2] optical filters,[3-5] and GaAs distributed feedback lasers.[6,7]

An analysis of the performance of injection semiconductor lasers with a corrugated interface[8] indicates the possibility of large reductions in the threshold current density as well as longitudinal and transverse mode discrimination.

As an intermediate step in the process of fabricating periodic semiconductor injection lasers we studied the feasibility of growing an epitaxial film of GaAlAs on a corrugated GaAs substrate. In the following we describe some of the results obtained using liquid phase epitaxy.

The substrates used were Te-doped GaAs (100) wafers with a carrier density of 10^{18} cm^{-3}. After mirror polishing we fabricated mechanical corrugations with periods of 0.115 or 0.35 μm on the surface using the technique of ion milling through a photoresist mask which was produced by laser beam interference.[9] The depth of the corrugations on the various samples ranged between 500 and 600 Å.

Ge-doped (or undoped) GaAlAs layers were grown on the GaAs corrugated surfaces by liquid phase epitaxy using a slide boat. The mole fraction of Al was 0.5–0.7 in the epitaxial layers. The growth system used in this experiment had small horizontal temperature gradients and minimal vertical gradients. After prebaking, the system was cooled by 10 °C at a cooling rate of 1–5 °C/min, and then the substrate was moved into the Ga melt. Initial contact temperature ranged between 820 and 700 °C with a growth interval of 10–30 °C. The contact temperature was found to be the most important single parameter determining the amount of meltback.

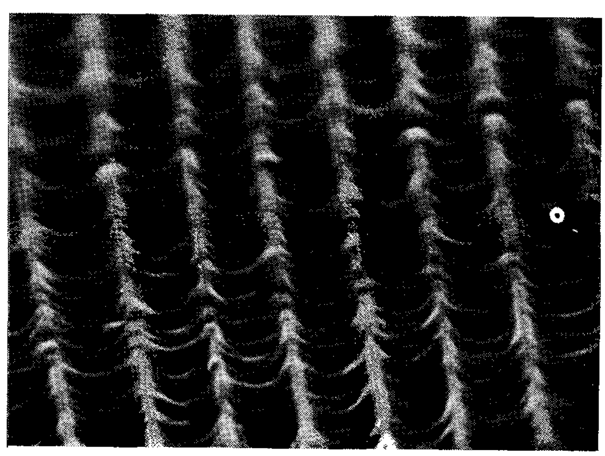

FIG. 1. SEM photograph of a GaAs corrugated surface before the growth. The period is 0.35 μm and the depth is 580 Å.

FIG. 2. SEM picture of GaAlAs on GaAs corrugated substrate. A part of the epitaxial layer was removed by HF. The small holes and the irregular edge were caused by HF during the partial etching.

A SEM photograph of a corrugated substrate prior to growing is shown in Fig. 1. The period is 0.35 μm and the corrugation depth is 580 Å.

The surface of the epitaxial GaAlAs grown above 700 °C on the corrugated substrate had a mirrorlike finish. In order to investigate the structure of the interface, we removed part of the epitaxial layer by HF to expose the corrugations which were then photographed by a scanning electron microscope (SEM). Figure 2 shows an example of a photograph taken by this method. In this case the GaAlAs layer was grown from 700 to 670 °C at a cooling rate of 5 °C/min. The surface corrugation survived nearly intact with only minimal meltback. The irregular edge and the small holes in the epitaxial layer of Fig. 2 were caused by penetration of HF through the imperfect mask.

SEM pictures of the corrugated interfaces were also taken using cleaved surfaces and an example is shown in Fig. 3. The contrast near the interface is due to the difference in Al concentration. The measured depth of the corrugation in this case is 500 Å, to be compared with a value of 580 Å before the growth. It is important to note in this figure the lack of interface defects.

The dependence of the amount of the meltback on the growth conditions was investigated by growing epitaxial layers under a variety of conditions, and the results are listed in Table I. A great deal of improvement in reducing the amount of the meltback was achieved by lowering the contact temperature. For example, the depth of the corrugation after the growth was 500 Å with a growth temperature range of 700–670 °C, while it was $\lesssim 100$ Å with 820–800 °C. A small improvement was also obtained by increasing the cooling rate from 1 to 5 °C/min.

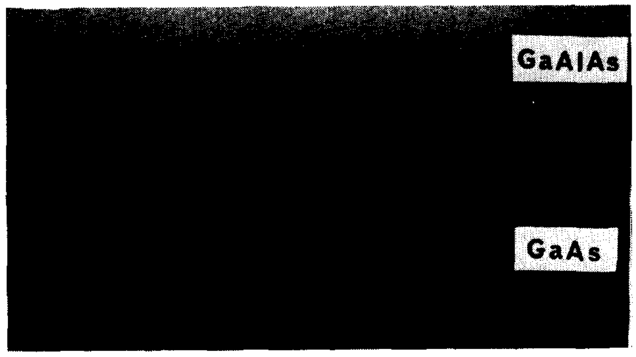

FIG. 3. SEM picture of a cleaved surface.

The depth of the corrugation was also evaluated indirectly by measuring the intensity of the diffracted light from the corrugation after removing the epitaxial layers. A He-Ne laser (6328 Å) was used in this experiment, where the polarization of the input light was in the incident plane. The diffraction intensity was measured at a diffraction angle of 65°. The diffraction efficiency (the ratio of diffraction intensity to input intensity) is shown for each sample in Table I. High diffraction efficiencies were obtained by starting the growth at temperatures below 750 °C. The efficiency was 8% in the best sample (A-5), down from a value of 10% before the growth.

The *I-V* characteristics of the corrugated *p-n* junctions were measured by making Ohmic contacts with Au-Ge-Ni on *n*-GaAs and Ti-Au on *p*-GaAlAs. The results were substantially identical to those obtained from uncorrugated GaAs substrates by the same method, supporting the observation of a high-quality interface.

Similar results were obtained on substrates with surface corrugations of 0.115 μm.

In conclusion, liquid phase epitaxy of GaAlAs was performed on GaAs corrugated substrates. It was confirmed from the SEM observation of the interface and measurements of diffraction efficiency that the epitaxial layers were successfully grown with marked reduction of the meltback by optimizing the growth conditions. We may also point out that the buried periodic layer obtained by this technique may represent an alternate approach for obtaining "superlattices".[10]

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TABLE I. Dependence of the corrugation depth and the diffraction efficiency on growth conditions.

Sample No.	Growth temperature range (°C)	Cooling rate (°C/min)	Final corrugation height peak-to-peak (Å)	Diffraction efficiency
A-1	820–810	1	<100	5×10^{-4}
A-2	820–810	5	100	1×10^{-3}
A-4	750–720	5	400	4×10^{-2}
A-5	700–670	5	500	8×10^{-2}
	before growth		580	1×10^{-1}

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Pulse compression for more efficient operation of solid-state laser amplifier chains*

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We propose a pulse compression scheme which reduces the peak intensity while increasing the energy density achievable in a Nd:glass amplifier chain. Self-focusing is the dominant effect responsible for limiting the power of a short-pulse Nd:glass amplifier chain, and the reduction of the intensity (through this compression scheme) greatly reduces these problems. We recommend injecting a lower-intensity and longer-duration pulse into the chain. Under some circumstances, the glass nonlinearity will impress upon the pulse a chirp suitable for efficient subsequent temporal compression, and this may result in higher effective peak power operation. If a 1-nsec (full $1/e$ duration) temporally Gaussian pulse with a chain-averaged peak intensity of 2 GW/cm^2 propagates 2 m in a Nd:glass laser chain, we calculate that the pulse could be subsequently compressed (by a series of Gires-Tournois interferometers) to 125 psec with good stability against input pulse amplitude noise. Such short pulses are of major interest for laser fusion.

In order to circumvent the intensity limitations due to self-focusing in a Nd:glass laser chain, we present a pulse compression scheme.[1] This consists of the use of a longer-duration and less intense pulse in the laser amplifier chain, followed by the use of a dispersive structure to temporally compress the "chirped" pulse after it exits the laser chain. In order to prepare the pulse for compression, the nonlinear index of refraction (n_2) of the host glass chirps the pulse and broadens the spectrum through self-phase modulation.

Optical pulse compression schemes analogous to those for radar pulses were independently proposed in the last decade.[2-4] It is of special interest here that unchirped laser pulses may be temporally compressed by first passing them through a nondispersive optical Kerr material, and subsequently passing them through an anomalously dispersive structure.[4] An experimental demonstration of this technique has been reported by Laubereau.[5]

With a computer simulation of propagation in a Nd:glass laser amplifier chain, we find that the pulse compression scheme described in Ref. 4 is operative when the laser amplifier chain serves as the nonlinear material or "chirper". As our example, we address our attention to the task of making more efficient use of Nd:glass laser chains for preliminary laser fusion experiments (which will require 10^4-J pulses with durations of approximately[6] 100 psec). Since the cost of capacitors, flashlamps, and glass for such a 10^4-J laser system depends nearly inversely upon the laser pulse duration,[7] the savings through such a compression scheme can be considerable. We also feel that the technique described here may improve the temporal resolution of the laser moon-ranging effort.[8]

As an example, first consider the simpler case[4] in which self-phase modulation of an initially temporally Gaussian pulse in nondispersive undoped glass causes a chirp to be impressed on the pulse. R, the ratio of pulse durations before and after optimal delay line compression, is estimated by comparison of spectral widths of input and output pulses, and we find $R = 1 + 0.86 k_0 l \delta n_{\max}/n_0$. Here n_0 is the linear index of refraction of the material evaluated at frequency ω_0, k_0 is given by $\omega_0 n_0/c$, l is the propagation length, and $\delta n_{\max}$ is the maximum nonlinear index change. Upon subsequent passage through a dispersive delay line, the compressed complex electric field of the pulse is given by[4]

$$E_c(t) = [\exp(-i\omega_0 t)/2\pi] \times \iint_{-\infty}^{\infty} dt'\, d\Omega\, \mathcal{E}(t') \exp\{i[\Omega(t'-t) + \delta\phi(t') + Q_2\Omega^2 + Q_3\Omega^3 + \cdots]\}, \quad (1)$$